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We state this in terms of colorings of edges of graphs.

*For all 2-coloring of the edges of $K_6$ there is a mono $K_3$. 

Let's Party Like It's January of 2019
Recall the first theorem one usually hears in Ramsey Theory and can tell your non-math friends about. 

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We state this in terms of colorings of edges of graphs.

*For all 2-coloring of the edges of $K_6$ there is a mono $K_3$.**

**Question** What if we color the edges of $K_5$?
Coloring of $K_5$ with no Mono $K_3$

This graph is not arbitrary.

$SQ_5 = \{x^2 \mod 5 : 0 \leq x \leq 4\} = \{0, 1, 4\}$.

- If $i - j \in SQ_5$ then RED.
- If $i - j \notin SQ_5$ then BLUE.
Asymmetric Ramsey Numbers

**Definition** $R(a,b)$ is least $n$ such that for all 2-colorings of $K_n$ there is either a red $K_a$ or a blue $K_b$.

1. $R(a,b) = R(b,a)$.
2. $R(2,b) = b$
3. $R(a,2) = a$
Theorem $R(a, b) \leq R(a - 1, b) + R(a, b - 1)$

Proof
Let $n = R(a - 1, b) + R(a, b - 1)$. $COL : ([n]) \rightarrow [2]$.

Case 1 ($\exists v)[\deg_R(v) \geq R(a - 1, b)]$. Look at the $R(a - 1, b)$ vertices that are RED to $v$. By Definition of $R(a - 1, b)$ either
- There is a RED $K_{a-1}$. Combine with $v$ to get RED $K_a$.
- There is a BLUE $K_b$.
\[ R(a, b) \leq R(a - 1, b) + R(a, b - 1) \]

**Theorem** \( R(a, b) \leq R(a - 1, b) + R(a, b - 1) \)

**Proof**

Let \( n = R(a - 1, b) + R(a, b - 1) \). COL : \( \binom{[n]}{2} \rightarrow [2] \).

**Case 1** \( \exists v \) \( \deg_R(v) \geq R(a - 1, b) \). Look at the \( R(a - 1, b) \) vertices that are RED to \( v \). By Definition of \( R(a - 1, b) \) either

- There is a RED \( K_{a-1} \). Combine with \( v \) to get RED \( K_a \).
- There is a BLUE \( K_b \).

**Case 2** \( \exists v \) \( \deg_B(v) \geq R(a, b - 1) \). Similar to Case 1.
\[ R(a, b) \leq R(a - 1, b) + R(a, b - 1) \]

**Theorem** \( R(a, b) \leq R(a - 1, b) + R(a, b - 1) \)

**Proof**

Let \( n = R(a - 1, b) + R(a, b - 1) \). \( \text{COL} : ([n]) \rightarrow [2] \).

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- There is a RED \( K_{a-1} \). Combine with \( v \) to get RED \( K_a \).
- There is a BLUE \( K_b \).

**Case 2** \( (\exists v) \left[ \text{deg}_B(v) \geq R(a, b - 1) \right] \). Similar to Case 1.

**Case 3**

\( (\forall v) \left[ \text{deg}_R(v) \leq R(a - 1, b) - 1 \wedge \text{deg}_B(v) \leq R(a, b - 1) - 1 \right] \)

\( (\forall v) \left[ \text{deg}(v) \leq R(a - 1, b) + R(a, b - 1) - 2 = n - 2 \right] \)

Not possible since every vertex of \( K_n \) has degree \( n - 1 \).
Let's Compute Bounds on $R(a, b)$

- $R(3, 3) \leq R(2, 3) + R(3, 2) \leq 3 + 3 = 6$
- $R(3, 4) \leq R(2, 4) + R(3, 3) \leq 4 + 6 = 10$
- $R(3, 5) \leq R(2, 5) + R(3, 4) \leq 5 + 10 = 15$
- $R(3, 6) \leq R(2, 6) + R(3, 5) \leq 6 + 15 = 21$
- $R(3, 7) \leq R(2, 7) + R(3, 6) \leq 7 + 21 = 28$
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Can we make some improvements to this?
Let's Compute Bounds on $R(a, b)$

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Can we make some improvements to this? YES!
Theorem $R(3, 4) \leq 9$.

Let $COL$ be a 2-coloring of the edges of $K_9$.

Case 1 ($\exists v)[\deg_R(v) \geq 4]$. $v_1, \ldots, v_4$ are RED to $v$.
\[ R(3, 4) \leq 9 \]

**Theorem** \( R(3, 4) \leq 9. \)

Let \( \text{COL} \) be a 2-coloring of the edges of \( K_9 \).

**Case 1** \((\exists v)[\deg_R(v) \geq 4]\). \( v_1, \ldots, v_4 \) are RED to \( v \).

If any of \( v_i, v_j \) is RED, then \( v, v_i, v_j \) are RED \( K_3 \).

**Case 2** \((\exists v)[\deg_B(v) \geq 6]\). \( v_1, \ldots, v_6 \) are BLUE to \( v \).

Either:
1. a RED \( K_3 \), or
2. a BLUE \( K_3 \), which together with \( v \) is a BLUE \( K_4 \).

**NOTE** Can't have any \( \deg_R(v) \leq 2 \).

**Case 3** \((\forall v)[\deg_R(v) = 3]\). The RED subgraph has 9 nodes each of degree 3. Impossible!
\textbf{Theorem} \( R(3, 4) \leq 9 \).

Let \( \text{COL} \) be a 2-coloring of the edges of \( K_9 \).

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Theorem $R(3, 4) \leq 9$.

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Case 2 ($\exists v$)[deg$_B(v) \geq 6$]. $v_1, \ldots, v_6$ are BLUE to $v$. Either:
(1) a RED $K_3$, or
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Lemma Let $G = (V, E)$ be a graph.

\[ V_{\text{even}} = \{ v : \deg(v) \equiv 0 \pmod{2} \} \]
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Then $|V_{\text{odd}}| \equiv 0 \pmod{2}$. 
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Recall that for any graph $G = (V, E)$:

$$\sum_{v \in V_{\text{even}}} \deg(v) + \sum_{v \in V_{\text{odd}}} \deg(v) = \sum_{v \in V} \deg(v) = 2|E| \equiv 0 \pmod{2}.$$
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\]

\[
\sum_{v \in V_{\text{odd}}} \deg(v) \equiv 0 \pmod{2}.
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Sum of odds $\equiv 0 \pmod{2}$. Must have even numb of them. So $|V_{\text{odd}}| \equiv 0 \pmod{2}$. 

A Generalization of this Trick

What was it about $R(3, 4)$ that made that trick work?
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We originally had

$$R(3, 4) \leq R(2, 4) + R(3, 3) \leq 4 + 6 \leq 10$$
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**Key:** $R(2, 4)$ and $R(3, 3)$ were both even!
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**Key:** $R(2, 4)$ and $R(3, 3)$ were both even!

**Theorem** $R(a, b) \leq$

1. $R(a, b - 1) + R(a - 1, b)$ always.
2. $R(a, b - 1) + R(a - 1, b) - 1$ if
   $R(a, b - 1) \equiv R(a - 1, b) \equiv 0 \pmod{2}$
Some Better Upper Bounds

- $R(3, 3) \leq R(2, 3) + R(3, 2) \leq 3 + 3 = 6.$
- $R(3, 4) \leq R(2, 4) + R(3, 3) \leq 4 + 6 - 1 = 9.$
- $R(3, 5) \leq R(2, 5) + R(3, 4) \leq 5 + 9 = 14.$
- $R(3, 6) \leq R(2, 6) + R(3, 5) \leq 6 + 14 - 1 = 19.$
- $R(3, 7) \leq R(2, 7) + R(3, 6) \leq 7 + 19 = 26.$
- $R(4, 4) \leq R(3, 4) + R(4, 3) \leq 9 + 9 = 18.$
- $R(4, 5) \leq R(3, 5) + R(4, 4) \leq 14 + 18 - 1 = 31.$
- $R(5, 5) \leq R(4, 5) + R(5, 4) = 62.$

Are these tight?
$R(3, 3) \geq 6$

$R(3, 3) \geq 6$: Need coloring of $K_5$ w/o mono $K_3$. 

Note $-1 = 2^2 \pmod{5}$. Hence $a - b \in \text{SQ}$ iff $b - a \in \text{SQ}$. So the coloring is well defined.
$R(3, 3) \geq 6$

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Vertices are $\{0, 1, 2, 3, 4\}$.
\[ R(3, 3) \geq 6 \]

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Vertices are \( \{0, 1, 2, 3, 4\} \).

\[ \text{COL}(a, b) = \text{ RED if } a - b \equiv SQ \pmod{5}, \text{ BLUE OW.} \]
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**Note** $-1 = 2^2 \pmod{5}$. Hence $a - b \in SQ$ iff $b - a \in SQ$. So the coloring is well defined.
\( R(3, 3) \geq 6 \)

\[ COL(a, b) = \text{RED if } a - b \equiv SQ \pmod{5}, \text{BLUE otherwise.} \]

- Squares mod 5: 1, 4.
- If there is a RED triangle then \( a - b, b - c, c - a \) all SQ’s. SUM is 0. So

\[ x^2 + y^2 + z^2 \equiv 0 \pmod{5} \text{ Can show impossible} \]

- If there is a BLUE triangle then \( a - b, b - c, c - a \) all non-SQ’s. Product of nonsq’s is a sq. So

\[ 2(a - b), 2(b - c), 2(c - a) \] all squares. SUM to zero- same proof.

**UPSHOT** \( R(3, 3) = 6 \) and the coloring used math of interest!
$R(4, 4) = 18$

$R(4, 4) \geq 18$: Need coloring of $K_{17}$ w/o mono $K_4$. 
\( R(4, 4) = 18 \)

\( R(4, 4) \geq 18 \): Need coloring of \( K_{17} \) w/o mono \( K_4 \).

Vertices are \( \{0, \ldots, 16\} \).

Use \\
\( \text{COL}(a, b) = \text{RED if } a - b \equiv SQ \pmod{17}, \text{BLUE OW.} \)
$R(4, 4) = 18$

$R(4, 4) \geq 18$: Need coloring of $K_{17}$ w/o mono $K_4$.

Vertices are $\{0, \ldots, 16\}$.

Use
\[ COL(a, b) = \text{RED if } a - b \equiv SQ \pmod{17}, \text{BLUE OW}. \]

Same idea as above for $K_5$, but more cases.

**UPSHOT** $R(4, 4) = 18$ and the coloring used math of interest!
\( R(3, 5) = 14 \)

\[ R(3, 5) \geq 14: \text{Need coloring of } K_{13} \text{ w/o RED } K_3 \text{ or BLUE } K_5. \]
$R(3, 5) = 14$

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Vertices are $\{0, \ldots, 13\}$.

Use

$COL(a, b) = \text{RED}$ if $a - b \equiv \text{CUBE} \pmod{17}$, BLUE OW.
\[ R(3, 5) = 14 \]

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Vertices are \{0, \ldots, 13\}.

Use
\[ \text{COL}(a, b) = \text{RED if } a - b \equiv \text{CUBE (mod 17)}, \text{ BLUE OW.} \]

Same idea as above for \( K_5 \), but more cases.
$R(3, 5) = 14$

$R(3, 5) \geq 14$: Need coloring of $K_{13}$ w/o RED $K_3$ or BLUE $K_5$.

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**UPSHOT** $R(3, 5) = 14$ and the coloring used math of interest!
$R(3, 4) = 9$

This is a subgraph of the $R(3, 5)$ graph
$R(3, 4) = 9$

This is a subgraph of the $R(3, 5)$ graph

**UPSHOT** $R(3, 4) = 9$ and the coloring used math of interest!
Can we extend these Patterns?

**Good news** $R(4, 5) = 25$. 

**Bad news** THAT’S IT. No other $R(a, b)$ are known using NICE methods. $R(5, 5)$—More on that later.
Can we extend these Patterns?

**Good news** \( R(4, 5) = 25. \)

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\( R(5, 5) \)—More on that later.
Revisit those Numbers


- $R(3, 3) \leq 6$. TIGHT. Int
- $R(3, 4) \leq 9$. TIGHT. Int
- $R(3, 5) \leq 14$. TIGHT. Int
- $R(3, 6) \leq 19$. KNOWN: 18. Upper Bd Bor, Lower Bd Int
- $R(3, 7) \leq 26$. KNOWN: 23. Upper Bd Bor, Lower Bd Int
- $R(4, 4) \leq 18$. TIGHT. Int
- $R(4, 5) \leq 31$. KNOWN: 25. Both bd Bor
- $R(5, 5) \leq 62$. KNOWN: Between 43 and 49. Both Bor.
Moral of the Story (Due Tuesday?)

1. At first there seemed to be interesting mathematics with mods and primes leading to nice graphs.

[Joel Spencer] The Law of Small Numbers: Patterns that persist for small numbers will vanish when the calculations get to hard.

Seemed like a nice Math problem that would involve interesting and perhaps deep mathematics. No. The work on it is interesting and clever, but (1) the math is not deep, and (2) progress is slow.
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Moral of the Story (Due Tuesday?)

1. At first there seemed to be interesting mathematics with mods and primes leading to nice graphs. (Joel Spencer) *The Law of Small Numbers: Patterns that persist for small numbers will vanish when the calculations get to hard.*

2. Seemed like a nice Math problem that would involve interesting and perhaps deep mathematics. No. The work on it is interesting and clever, but (1) the math is not deep, and (2) progress is slow.
1. (Quote from Joel Spencer): Erdos asks us to imagine an alien force, vastly more powerful than us, landing on Earth and demanding the value of $R(5, 5)$ or they will destroy our planet. In that case, he claims, we should marshal all our computers and all our mathematicians and attempt to find the value. But suppose, instead, that they ask for $R(6, 6)$. In that case, he believes, we should attempt to destroy the aliens.
When Will We Know $R(5,5)$

1. (Quote from Joel Spencer): *Erdos asks us to imagine an alien force, vastly more powerful than us, landing on Earth and demanding the value of $R(5,5)$ or they will destroy our planet. In that case, he claims, we should marshal all our computers and all our mathematicians and attempt to find the value. But suppose, instead, that they ask for $R(6,6)$. In that case, he believes, we should attempt to destroy the aliens.*

2. I asked Stanislaw Radziszowski, the world’s leading authority on Small Ramsey Numbers, what $R(5,5)$ is and when we would know it. He said its 43 and we will *never* know it.
We Already Know $R(5, 5)!$

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A Nice Case of Interdisciplinary Research

https://blog.computationalcomplexity.org/2013/04/a-nice-case-of-interdisciplinary.html

Blog claimed a breakthrough: $R(5, 5)$ is now known! The breakthrough came via interdisciplinary research in
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5. Some people have fallen for it. Will tell stories in class.